CALIPSO SATELLITE LIDAR IDENTIFICATION OF ELEVATED DUST OVER AUSTRALIA COMPARED WITH AIR QUALITY MODEL PM60 FORECASTS

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ABSTRACT

Global measurements of the vertical distribution of clouds and aerosols have been recorded by the lidar on board the CALIPSO (Cloud Aerosol Lidar Infrared Pathfinder Satellite Observations) satellite since June 2006. Such extensive, height-resolved measurements provide a rare and valuable opportunity for developing, testing and validating various atmospheric models, including global climate, numerical weather prediction, chemical transport and air quality models.

Here we report on the initial results of an investigation into the performance of the Australian Air Quality Forecast System (AAQFS) model in forecasting the distribution of elevated dust over the Australian region. The model forecasts of PM60 dust distribution are compared with the CALIPSO lidar Vertical Feature Mask (VFM) data product. The VFM classifies contiguous atmospheric regions of enhanced back-scatter as either cloud or aerosols. Aerosols are further classified into six subtypes. By comparing forecast PM60 concentration profiles to the spatial distribution of dust reported in the CALIPSO VFM, we can assess the model's ability to predict the occurrence and the vertical and horizontal extents of dust events within the study area.

1. INTRODUCTION

The CALIPSO satellite, operational since June 2006, flies at an altitude of 705 km in a polar, circular, sun-synchronous orbit, with an orbital inclination of 98.2 degrees and an equatorial crossing time (ascending node) around 1330 local time. The satellite flies in formation with four other satellites as part of the A-Train constellation with the aim of making measurements of clouds and aerosols that will enable a better understanding of their effects on the global climate. The primary instrument carried by CALIPSO is a dual-wavelength (1064-nm and 532-nm), dual-polarization, backscatter lidar [1], which provides a global data set of range-resolved profiles of the distribution and optical properties of cloud and aerosol layers. In addition to the heights of cloud and aerosol layers, information on the shape of the particles in a layer can be obtained from the ratio of the signals in the two polarization channels, allowing spherical particles, as found in water clouds and hydrated aerosol layers to be distinguished from ice crystals and irregular dust particles. The ratio of the backscatter signals at the two wavelengths provides information on the relative sizes of particles and helps discriminate clouds from aerosols. The depolarization ratio, together with the integrated attenuated backscatter, latitude and surface type, allows a degree of classification of aerosol features into sub-types, in particular the identification of dust layers.

The ability of CALIPSO to provide global, height-resolved maps of the distribution of clouds and aerosols provides an ideal opportunity for the development, testing and validation of various atmospheric models. Here we report on the results of a small pilot study in which forecasts by the Australian Air Quality Forecast System (AAQFS) model [2] of the distribution of lofted dust over the Australian region are compared with CALIPSO measurements as reported in the CALIPSO VFM product version 2.01.

The primary aims of this current work are to assess the ability of the model to forecast dust events and to forecast the vertical and horizontal distribution of the dust. Once validated particulate extinction data are available from CALIPSO, an additional attempt will be made to compare forecast dust concentrations with concentrations deduced from the lidar extinction data.

2. METHODS

The creation of the CALIPSO Vertical Feature Mask requires the successful completion of several complex steps in the analysis of the lidar data. Data are first calibrated, and then the calibrated signals are analyzed by a Feature Finder to detect and demarcate layer boundaries. The layers are then classified as either clouds or aerosols and, finally, the clouds and aerosols are assigned to various subtypes. The classification and sub-typing of each layer, along with an indicator of the confidence in these classifications, are included in the VFM. As these processes are detailed in the corresponding Algorithm Theoretical Basis Documents

available on the CALIPSO website at http://www-calipso.larc.nasa.gov/resources/project_documentation.php, only the salient features are given here.

The Feature Finder inspects calibrated attenuated backscatter profiles and attempts to detect and determine the extent of clouds and aerosols. Analysis is performed on consecutive series of 240 profiles extending 80 km along the CALIPSO orbit track. Because atmospheric features vary over a wide range of spatial scales and backscatter intensities, the algorithm makes multiple passes through the data. The CALIPSO Feature Finder uses a selective, iterated boundary location (SIBYL) algorithm that detects layers at increasingly coarse spatial resolutions, corresponding to increasing amounts of horizontal averaging. Following each stage, the algorithm removes all layers detected within each profile, and rescales the signal below by (an estimate of) the layer attenuation. These modified profiles are then averaged (excluding those regions of the profiles in which previously detected features were removed) up to the next, coarser, horizontal resolution, and the feature detection process repeated. The final product includes layers detected at single-profile, 1-km, 5-km, 20-km and 80-km horizontal resolutions.

The Cloud Aerosol Discrimination (CAD) algorithm classifies layers as either clouds or aerosols by applying a confidence function to the information provided by the Feature Finder. This confidence function relies on a set of predetermined cloud and aerosol probability distribution functions (PDFs), which in turn are altitude-dependent functions of layer-averaged 532-nm attenuated backscatter and layer integrated attenuated total color ratio (i.e., the ratio of the layer-averaged backscatter at 1064 nm to that at 532nm). Depending on the value of its confidence function, a feature is determined to be either a cloud or an aerosol layer. In the version 2 CAD algorithm, the layer-integrated depolarization ratio is used as an additional check to prevent the misclassification of thin clouds as aerosol layers.

The aerosol classification algorithm uses the input parameters — altitude, location, surface type, volume depolarization ratio (δ_v), and the integrated attenuated backscatter (γ') — to identify the aerosol sub-type following one of several pathways. The depolarization ratio is used to identify aerosol types that have a substantial mass fraction of non-spherical particles, e.g., a mixture of smoke and dust, while γ' is used to discern instances of transient high aerosol loading over surfaces where this is not usually expected, e.g., a smoke or dust layer over land or the ocean. For aerosols in polar regions, the algorithm takes into consideration the high aerosol loading events caused by Arctic haze. The aerosol classification scheme thus identifies aerosol type, to the extent possible, from among one of the six types: desert dust, biomass burning (smoke), background (clean continental), polluted continental, marine and polluted dust. The aerosol subtype product depends critically on the preceding CAD analysis. If a cloud is mistakenly classified as an aerosol, the aerosol subtype algorithm will still assign this 'aerosol' to one of the aerosol subtypes. The user must exercise caution where the aerosol subtype looks suspect. This is most prevalent in the polar regions. Note that the VFM includes confidence flags for the various classifications that are assigned.

The Australian Air Quality Forecasting System is a twice-daily operational system that consists of five major components: a numerical weather prediction system known as the Limited Area Prediction system (LAPS), an emission inventory module, a chemical transport module (CTM), an evaluation module, and a data archiving and display module. For Australia-wide forecasts (http://www.dar.csiro.au/ozaaqfs/), AAQFS predicts daily wind-blown dust and fire smoke. The photochemistry and the emissions inventory for gaseous and particle species other than wind-blown dust are deactivated. The Australia-wide AAQFS modeling uses a horizontal resolution of 0.25° and 17 vertical levels (of varying thickness) up to 4.1km while LAPS uses a horizontal grid spacing of 0.125° and 29 vertical levels extending to 20 km.

The AAQFS dust emission module is based on a saltation bombardment scheme [3] that calculates a threshold friction velocity, horizontal sand flux and vertical dust flux. These are functions of soil and land surface characteristics and the climate and weather conditions. The AAQFS-CTM considers 25 dust particle classes in the range 2-125 μm and outputs dust size fractions up to 60 μm. The AAQFS outputs are linearly interpolated in time and space from the computational mesh to the CALIPSO trajectory for a given day.

3. RESULTS

Although the analysis of the data is still in progress, the results so far have provided very useful qualitative information, not only on the performance of the model, but also on the CALIPSO data and algorithms. As was expected, the analysis was not completely straight forward, with a number of factors preventing a direct assessment of the model's performance in all cases. Among these are meteorological conditions peculiar to many dust events and the limitations imposed on the CALIPSO analysis algorithms by the reduced signal-to-noise ratio (SNR) in some conditions.

In Australia, elevated dust occurs commonly during the passage of cold and gust fronts over the dry inland

regions. As such fronts are usually accompanied by dense clouds, many of these dust events are obscured from the CALIPSO lidar. There are many examples in the data where the CALIPSO VFM indicates the presence of dense cloud that attenuates the lidar signal completely and the model predicts a dust event in the same location. While the CALIPSO data cannot validate the model directly in these situations, the data do indicate that the model is predicting dust events in locations where interpretation of the CALIPSO VFM suggests that they are expected.

The creation of the CALIPSO VFM depends on the successful performance of the Feature Finder algorithm, which depends critically on accurate calibration of the data and on the SNR of the data. The reduced SNR in the stratospheric calibration region, combined with unexpected thermal effects due to the illumination of the satellite by sunlight, cause the CALIPSO daytime calibration constants to be less accurate than those for the nighttime orbit segments. Reflected sunlight from bright land surfaces, such as deserts, further degrades the SNR, and exacerbates the layer detection problem. Also, because the lidar signal is progressively attenuated as it passes through each overlying layer, the SNR of the signal backscattered from a dust layer situated below a cirrus cloud (for example) is also reduced. The result is that, in these situations, the Feature Finder sometimes does not detect the complete extent of a feature, or (rarely) misses it completely. Despite the restrictions imposed on our analysis by these complications, there are still sufficient examples of high-quality lidar data to provide ample opportunity for assessing the performance of the model.

The analysis so far has shown that the model is generally in qualitative agreement with the observations. A typical example is illustrated in Figure 1 where lidar data recorded as CALIPSO passed over Australia on the night of November 6th 2007 at around 1740 UTC are compared with the AAQFS model forecast for the same time and locations. The top panel shows the CALIPSO 1064-nm attenuated backscatter coefficients, in $(km.sr)^{-1}$, which have been averaged here to a horizontal resolution of 80 km (240 profiles) in order to accentuate the weak backscatter signals from aerosols, and plotted to an altitude of 4.5 km for comparison with the model outputs. Weak aerosol plumes can be seen above the clouds (backscatter > 0.01) between latitudes 10° – 16°, 20° – 28°, and 40° – 45°. The strong backscatter signal near zero altitude between 21° and 30° is the Australian continent. Regions identified by the Feature Finder in the Version 2.01 VFM as clouds and aerosols are plotted in the next panel. In the plot, a value of 1 (dark blue) indicates clear air, 2 (mid blue) clouds, 3 (pale blue) aerosols, 5 (orange) the surface, and 6 (magenta) regions where the signal has been totally attenuated by overlying features. It can be seen that, despite the weak backscatter signals in the top panel, the Feature Finder has successfully delineated the aerosol layers. The third panel indicates the CALIPSO aerosol subtypes as stored in the VFM. Features plotted in dark blue are identified as clean marine aerosols, mid blue as dust, pale blue as polluted continental, yellow as clean continental, orange as polluted dust and magenta as smoke. The plot shows that the elevated aerosol plume over the continent is identified by the CALIPSO algorithms as being predominantly dust and polluted dust, while the elevated plumes to the north and south of the Australian continent are classified as being predominantly smoke. Finally, the bottom panel shows the PM60 concentrations, in $\mu g.m^{-3}$, as forecast by the AAQFS model. As can be seen, there is a considerable degree of agreement between the observed and the forecast dust locations. The plume over the continent is accurately forecast by the model, and there is no elevated dust forecast north of the continent where CALIPSO identifies the plume as being predominantly smoke. The main area of disagreement is the model forecast of elevated dust south of the continent where CALIPSO identifies the aerosol plume as smoke. This could be either an incorrect forecast or a misclassification by the CALIPSO algorithm. Note that over the ocean, the aerosol sub-typing algorithm classifies all aerosol elevated above 1 km and with volume depolarization ratios less than 0.075 as smoke. Since not all these are smoke layers, the frequency of smoke layers over the ocean will be biased somewhat high especially in cases where water clouds are misidentified as aerosols in the CAD. Further analysis is required to resolve this anomaly. A second, lesser, area of inconsistency is seen in the different vertical extents of the measured and modeled plumes over the continent. This is by far the most common area of disagreement found in the analysis. On many occasions the dust plume is detected at altitudes above the maximum level of the model, and indicates that the model may need to include more levels and cover a greater height range if it is to forecast these dust events accurately.

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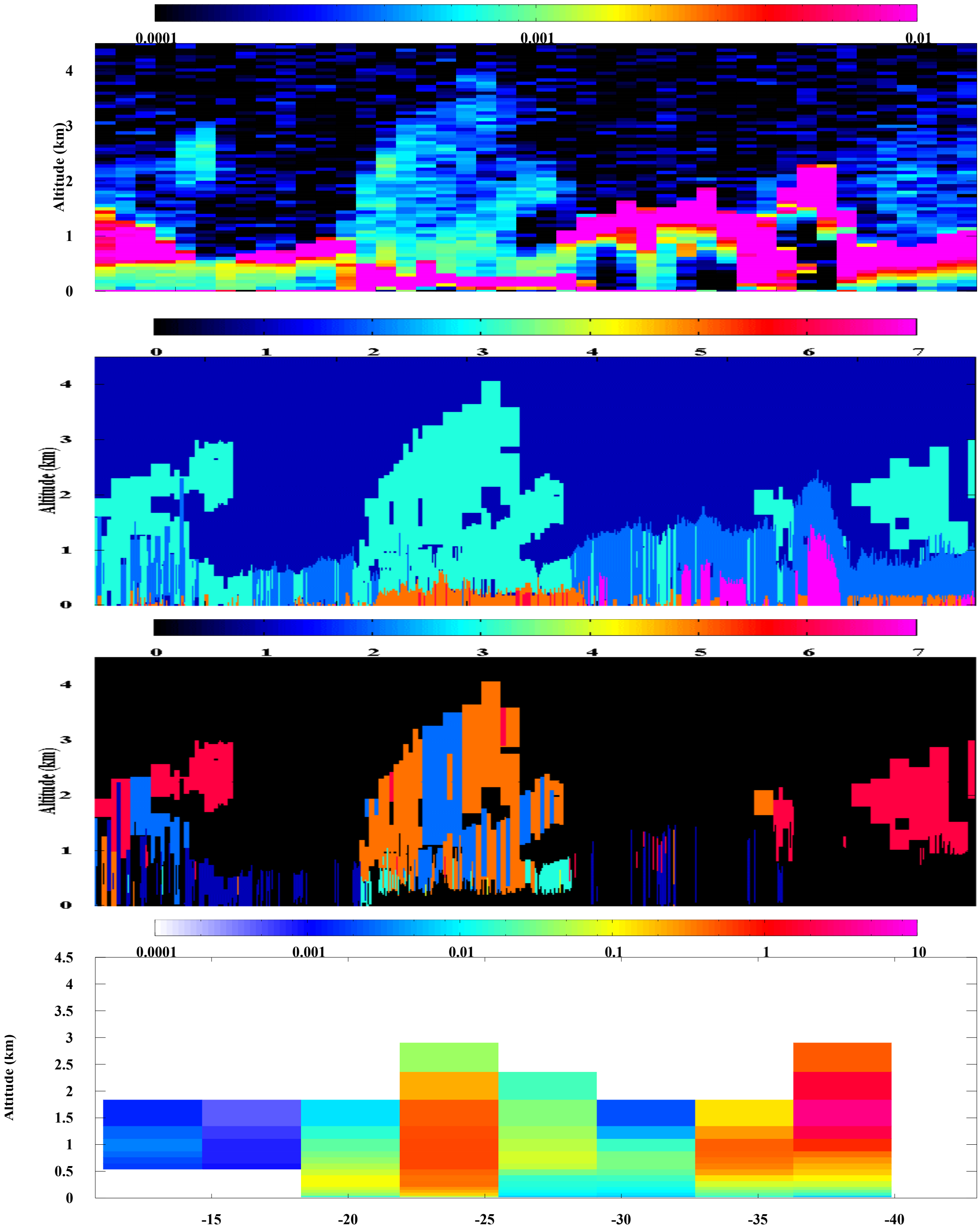

Figure 1. Top panel: CALIPSO 1064-nm attenuated backscatter $(km.sr)^{-1}$ recorded over Western Australia at around 1745 UTC on 6th November 2007. Second panel: CALIPSO Vertical Feature Mask showing clouds and aerosols. Third panel: CALIPSO Vertical Feature Mask showing the sub-types of features identified as aerosols. Bottom panel: The Australian Air Quality Forecast System Model forecasts of PM60 dust concentration in $\mu g.m^{-3}$. The same latitude scale applies to all panels. Color bars above each panel indicate plotted values. See text for details.